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Analog modeling of the formation of wrinkles on the upper surface of saucer-shaped sill intrusions

Kirsten Haaberg[1], Stéphane Polteau[1], Olivier Galland[1]
[1]Physics of Geological Processes, University of Oslo, Norway
E-mail: kirsten.haaberg@fys.uio.no, Tel.: +47-22-856053, http://www.fys.uio.no/pgp

Saucer shaped sills display undulating surfaces in seismic reflection data that can also be observed during fieldwork. In the Karoo basin, South Africa, saucer-shaped sills are exceptionally well exposed and can be studied in detail. The aim of this study is to develop an analog model in order to identify the parameters involved in undulating the upper surface. The analog modeling is constrained by field observations, geochemistry, and anisotropy of magnetic susceptibility (AMS). The undulations form folds that are present on several scales; from wavelengths of a few meters up to a couple of hundred of meters. Based on AMS analyses, the large scale undulations are the results of channeling of the magma flow that radiated generally outward from the center of the sill. The large scale undulation thus represents a primary emplacement feature. On the other hand, the small scale undulations wrinkle the upper surface of the sill. AMS analyses of the wrinkles show either peripheral flow direction or shearing of the margins of the sill. The wrinkles result from a reduction in intrusion volume. The chilled margins of the sill form a visco-elastic thin-film that wrinkles to accommodate the resulting volume reduction. The analog modeling is testing the possible mechanisms that will create a volume decrease responsible for the subsequent wrinkling. The mechanisms evaluated are one or a combination of:

1. Thermal contraction as the magma cools and crystallizes; a volume reduction of 10% is calculated using the density difference of basaltic melt and the Karoo dolerite (2,600 and 2,900 kg/m^3, respectively).
2. Post-emplacement collapse that will be triggered by a combination of back-flow of the magma as the injection ceases with drop in magmapressure. This is followed by the collapse of the sill under its ownweight causing shearing on the margins. Buckling is observed in the center of a smaller saucer shaped sill and might be the consequence of the magma flow back towards the center of the sill.

In conclusion, the overall morphology of saucer-shaped sills is primarily controlled by emplacement processes. However, constrained by analog modeling, the wrinkled morphology of the upper surface of the saucer-shaped sill is entirely controlled by post-emplacement volume reduction mechanism.

High-level sill and dyke intrusions initiated from rapidly buried mafic lava flows within scoria cones of Tongoa, Vanuatu (New Hebrides), South Pacific

Károly Németh[1], James D. L. White[2]
[1]Massey University, Institute of Natural Resources, P.O. Box 11 222, Palmerston North, New Zealand
E-mail: k.nemeth@massey.ac.nz
[2]University of Otago, Geology Department, PO Box 56, Dunedin, New Zealand
E-mail: james.white@otago.ac.nz

Scoria cones have been observed to grow rapidly in days to weeks. During their growth, lava flows may be fed onto the cone surface from lava-lake breaches, or form by coalescence of spatter. Such flows are preserved interbedded within scoria lapilli and ash beds of the cone. On Tongoa, an island of the Vanuatu volcanic arc in the South Pacific, a series of scoria cones developed during the Holocene, formed a widespread monogenetic volcanic field. Half sections of scoria cones along the coast expose complex interior cone architectures. On the western side of Tongoa Island a scoria cone remnant with steeply crater-ward dipping beds of scoria ash and lapilli contains various dm-to-m thick lava flows, which are connected by irregular dikes cutting obliquely across the beds of the cone. The lava flows are coherent igneous bodies with well-developed flow top and basal breccias. The lavas interbedded with the cone-forming layers are part of a larger (up to 7 m thick) body that is connected to dykes and sills of irregular geometries that intrude the cone's pyroclastic layers. This 3D relationship suggests that the lava flows were buried quickly under the accumulating scoriaceous deposits. This forces the escape of magma from the fluid interiors of flows, with the magma being squeezed upward or laterally into the accumulating pyroclastic pile. Movement of the pile above the partly mobile lava, and its potential destabilization by lava squeezed from the flows, may signal the onset of localized cone failures, and could be implicated in development of major cone breaches (e.g., at Paricutin).

Keywords: Strombolian · Scoria · Lava flow · Mafic · Peperite

Introduction

Central Vanuatu in the New Hebrides (South Pacific) is an active volcanic arc. Volcanic activity on the island of Tongoa (Fig. 1) is considered to be long lived, having extended through the Holocene to produce a predominantly mafic, monogenetic volcanic field through the island (Warden 1967). Holocene scoria cones and basaltic to andesitic lava flows are covered by younger dacitic

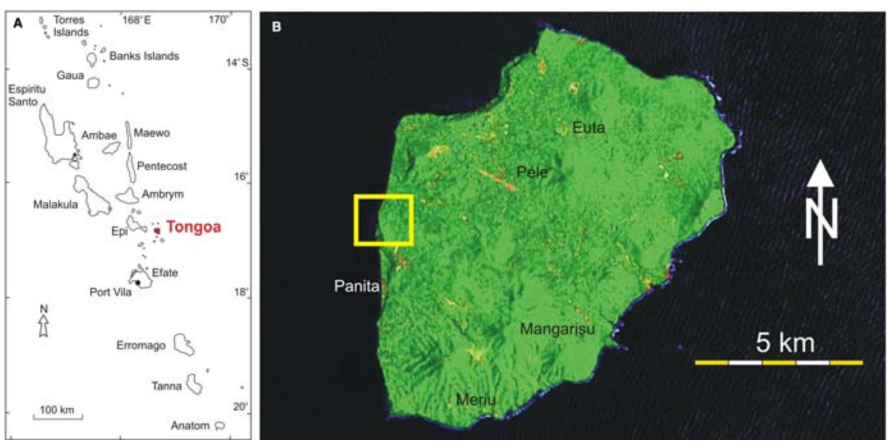

Fig. 1 Location map of the Vanuatu arc (**a**) and the island of Tongoa (MrSID satellite image) (**b**). *Yellow rectangle* shows the location of the studied scoria cone

pyroclastic successions, considered eruptive products of the Kuwae volcanic event (Monzier et al. 1994; Robin et al. 1994). The Holocene pre-Kuwae volcanics form a succession at least a 200 m thick of red scoriaceous ash and lapilli interbedded with agglomeratic units, and including decimeters- to meters-thick lava flows having flow top and basal breccias (Warden 1967). Half sections of scoria cones along the coastline expose complex scoria cone architectures, while gradual facies changes from proximal to distal areas and common textural changes from one bed to the next within the pyroclastic units; this variability is taken to indicate the influence of external water during most or all of the eruptions. On the western side of Tongoa (Fig. 1), an erosional remnant of a complex scoria cone exposes lava flows and associated intrusive bodies intruded into this volcanic cone as it was growing.

Lava flow-fed intrusions

Scoria cone growth is a generally rapid process that commonly takes place on timescales of days to weeks (Vespermann and Schmincke 2000). During scoria cone growth, the level of fragmentation of magma may change, coupled with fluctuations in conduit magma supply and the height of the eruption column (Houghton et al. 1999). The degree of vesiculation of the rising melt may also vary during scoria cone eruptions, with periods of more effective magma degassing in the conduit leading to reduced eruptive explosivity and occasional effusion of lava during scoria cone formation (Houghton et al. 1999). As a result, the scoria cone pyroclastic deposits are commonly interbedded with lava flows, many distinguished by well-developed brecciated flow tops and bases. It is also common for magma, or ponded lava, to escape beneath the lower-density cone deposits, breaching the volcanic edifice during the ongoing volcanic eruptions to trigger partial collapses of the cone (Feraud et al. 1999; Sumner 1998).

Scoria cone growth may also result in rapid burial of freshly erupted lava flows. On the western side of Tongoa, a scoria complex exposed in cliffs along the shoreline reveals the products of this process. Scoria cone pyroclastic beds comprise predominantly scoriaceous lapilli beds of cm-to-dm thickness (Fig. 2a), which dip steeply islandward. Bed-parallel coherent magmatic bodies of dm-to-m thickness, over- and underlain by coarse pyroclastic breccias, are interpreted as lava flows (Fig. 2b). Dykes extend upward and laterally from the lava flow, and their margins are irregular with a few-centimeter-thick chilled, black zone. The interiors of the intrusions are aphanitic and non-vesicular (Fig. 2c). Individual intrusions reach up to 15 m in length, and intrude 10 m into the overlying pyroclastic pile. This indicates that at least 10 m of scoria were deposited on this part of the cone before it was intruded by the magma squeezed from the partly molten lava flows buried on its flank. This suggests that scoria piles are able to effectively retain heat of the buried lava flows effectively or can accumulate so rapidly that they can bury flows within hours of their emplacement. Large lava flows in general may retain molten interior zones for several weeks (e.g., Hon et al. 1994). When flows become buried while their fluid cores remain active, the overburden can cause deformation of the flow margins to allow escape of the interior magma (e.g., at Paricutin–in Foshag and Gonzalez 1956). The buried lava flows in this section on Tongoa, and the associated complex of oblique dykes and sills above them, are also apparently related to local ponding of the lava on the cone flank, perhaps due to deformation beneath the growing cone flank (Fig. 2d). Along the margin of the intrusions the host scoriaceous pile is thermally altered and form reddish oxidized zones in the darker-colored scoriaceous deposits (Fig. 2c).

Conclusion

Lava-fed intrusions in a scoria cone, half section in Tongoa, attest to the very rapid growth of scoria cones. The features resulting from interaction of lava, scoria, and lava-sourced intrusions in the

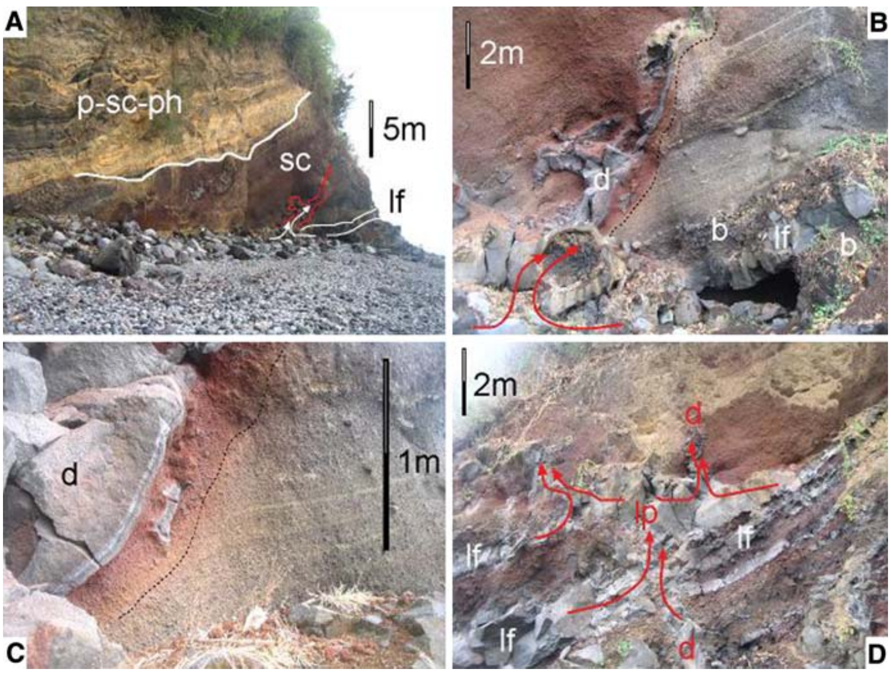

Fig. 2 **a** Overview of the scoria cone half-section in the western coastline of Tongoa. The *yellow* upper pyroclastic section (p-sc-ph) represents post-scoria cone phreatomagmatic pyroclastic deposits that consist of base surge and fall beds. The *white line* marks the lava flow (lf), and *red lines* represents the lava flow-fed dykes intruded into the scoria cone deposits (sc). **b** Close-up view of the lava flow (lf) and lava flow-fed dyke (d). Note the flow top and basal breccia over and under the lava flow (b). *Red arrows* mark the magma movement feeding the irregular shape sills intrude into the freshly deposited scoria ash and lapilli succession. **c** Irregular and curved dyke (d) margin. Note the thermal effect of the dyke on the scoriaceous deposits. **d** Complex lava flow (lf) and lava pond (lp) interaction in the scoria cone half section in Tongoa. Note the irregular dykes (d) fed from these lava flows

scoria cone in Tongoa show much small-scale complexity. Where this has occurred, the cone consists of a sheeted network of slope-parallel and steeply crosscutting coherent igneous rocks, autobreccia, and locally developed peperite, all intercalated with the host pyroclastic material. These outcrops also provide information of potential use in hazard evaluation. The dykes and sills developed from the lava suggest that the studied cone must have accumulated at least 10 m of scoria on top of a still–active buried lava flow. During the eruption this buried lava may have been invisible to onlookers, but it still had a fluid core capable of feeding lava to the surface beyond the zone of rapid burial, or, perhaps more importantly of causing collapse of a growing cone by deforming within it and injecting sheets of magma upward or laterally.

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Lava lakes and shallow magmatic feeding systems of mafic volcanoes of an ocean island Ambrym, Vanuatu (New Hebrides), South Pacific

Károly Németh, Shane J. Cronin
Massey University, Institute of Natural Resources, P.O. Box 11 222, Palmerston North, New Zealand
E-mail: k.nemeth@massey.ac.nz, s.j.cronin@massey.ac.nz

Ambrym is an oceanic arc-volcanic island with two major active vent complexes; Marum and Benbow. These vents have been active over at least the last 300 years, producing high-volume constant degassing interspersed by strombolian, sub-Plinian, and Vulcanian eruptions which are commonly associated with phreatomagmatic explosive phases. Inside the active vent pit-craters, cross-sections of the pyroclastic successions are commonly interbedded with apparently ponded lavas from old lava lakes. However, and of greater volumetric importance in some of the vent sequences, e.g., the Marum sub-vent Niri-Mbwelesu, are coherent intrusive bodies comprising inter-connected networks of sills and dykes. The large sills are connected through a complex network of pathways to the surface and/or into the pyroclastic edifice of the volcano. These structures suggest that shallow level infiltration of melt into a mafic volcano plays an important role in the growth of such apparently pyroclastic edifices.

Keywords: Mafic · Shield volcano · Phreatomagmatic · Pit crater · Lava spatter · Sill

Introduction

Ambrym Island is located in the central part of the Vanuatu volcanic arc and form a triangular, slightly E–W elongated island

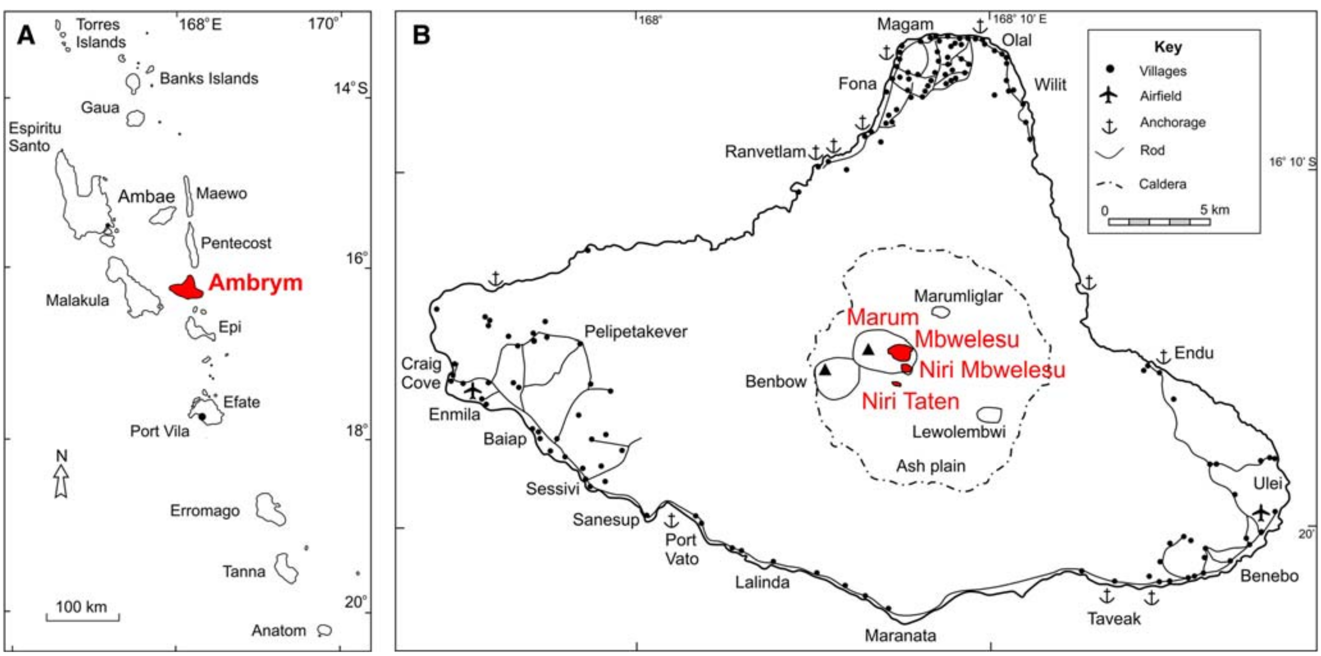

Fig. 1 Overview map of the Vanuatu arc (**a**) and Amrbym Island (**b**). *Red names* refer to the studied vents of the Marum volcanic complex

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High level sill and dyke intrusions initiated from rapidly buried mafic lava flows in scoria cones of Tongoa, Vanuatu (New Hebrides), South Pacific

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